DETAILED DESCRIPTION OF THE INVENTION

[0018] A description of various embodiments of the invention follows.

[0019] FIG. 1 illustrates an embodiment of an AAFO 10, an actuator 12, and sensors 14, 16 attached to a conventional AFO 18. In one embodiment, the AAFO 10 has a total weight of about 2.6 kg, excluding the weight of an off-board power supply. In a particular embodiment, the actuator 12 includes a Series Elastic Actuator (SEA), previously developed for legged robots, for controlling the impedance of the orthotic ankle joint for sagittal plane rotations. The SEA 12 can include a brushless DC motor in series with a spring. The SEA 12 provides force control by controlling the extent to which the series spring 20 is compressed. The deflection of the spring 20 can be measured by a linear potentiometer sampled at 1000 Hz and passed through a first order filter with a cutoff frequency equal to 50 Hz. The signal can be numerically differentiated and passed through another first order filter with a cutoff frequency of 8 Hz. The deflection of the series spring 20 can be controlled using a proportional-derivative (PD) controller.

[0020] Some advantages of the SEA 12 are that it has low impedance, the motor is isolated from shock loads, and the effects of backlash, torque ripple, and friction are filtered by the spring 20. A further advantage is that the SEA 12 exhibits stable behavior while in contact with most environments, even when in parallel with a human limb. In particular embodiments, the SEA 12 allows for the implementation of any virtual, torsion mechanical element about the ankle.

[0021] In a particular embodiment, the conventional AFO 18 includes a standard polypropylene AFO with a metallic hinge, such as a Scotty© ankle joint. This joint allows free motion in the sagittal plane (plantar and dorsiflexion) but is rigid for inversion/eversion movements. The AFO 18 can be modified by molding two recesses—one at the heel and the other at mid-calf. Several holes can be drilled in these recesses to attach the SEA 12.

[0022] In a particular embodiment, an ankle angle sensor 14 includes a Bourns 6637S-1-502 5 kΩ rotary potentiometer to determine the angle between a shank or leg portion 22, which is attachable to a person's foot, and the foot 24. The angle sensory signal can be sampled at 1000 Hz and passed through a first order low pass filter with a cutoff frequency of 50 Hz. The ankle velocity can be found by differentiating the pot signal and then passing it through a second order Butterworth filter with a cutoff frequency of 8 Hz. In another embodiment, the position of the orthotic ankle joint can be measured with a rotary encoder placed on the SEA 12. Such a sensor can measure motor position directly and orthotic position indirectly.

[0023] In other embodiments, Ground Reaction Force (GRF) sensors 16 can be used to measure forces on the foot 24. In a particular embodiment, an Ultraflex system can be used. In one embodiment, six capacitive force transducers, 25 mm square and 3 mm thick, can be placed on the bottom or foot 24 of the AFO 18, two sensors beneath the heel and four beneath the forefoot region. In particular embodiments, each sensor 16 can detect up to 1000 N, and can have a resolution of 2.5, and a scanning frequency of 125 Hz. The signal from each sensor 16 can be passed through a first-order filter with a cut-off frequency equal to 5 Hz. A single foot switch, model MA-153, can be placed in the heel of a shoe worn with the orthosis to detect heel strike approximately 30 ms earlier than the Ultraflex force sensors.

[0024] Ankle biomechanics for level ground walking on smooth surfaces can be described using four distinct walking phases. In this description, only sagittal rotations are described, that is to say, dorsi and plantarflexion and not inversion-eversion movements.

[0025] Beginning with heel strike, the stance ankle begins to plantarflex slightly. This flexion, called controlled plantarflexion, allows for a smooth heel-strike to forefoot-strike transition. Recent investigations show that the torque versus angle data are spring-like with ankle torque increasing linearly with ankle position. Although a normal, healthy ankle behaves as a passive mechanical linear spring within a contact phase, the stiffness of that linear spring is continually modulated by the central nervous system from step to step. It is believed that the body adjusts ankle spring stiffness to achieve a fixed energy absorption and release at each walking speed. Data also show that energy absorption and release increases with increasing walking speed, necessitating an increase in ankle stiffness with walking speed (when the heel-strike angle remains invariant to speed variations).

[0026] After maximum plantarflexion is reached in the stance ankle, the joint begins to dorsiflex. In this particular walking phase, called controlled dorsiflexion, the ankle also is spring-like but is distinctly nonlinear; here, ankle stiffness increases with increasing ankle dorsiflexion to gradually slow tibia progression.

[0027] During late stance, the ankle begins to power plantarflex to drive kinetic energy into the lower limb in preparation for the swing phase. For moderate to fast walking speeds, about 10-20 Joules of ankle work are performed. That energy is above and beyond the spring energies stored and released from early to late stance.

[0028] As the hip is flexed, and the knee has reached a certain angle in knee break, the leg leaves the ground and the knee continues to flex. Throughout the swing phase, the swing foot continues to rotate to cancel the angular momentum of the adjacent stance foot such that the net angular momentum contribution about the body's center of mass is zero.

[0029] A finite state machine can be implemented to address each complication of an ankle foot gait pathology, such as drop foot gait. Three states were used, each with a specific control objective (FIG. 2). Contact 1 spans the first half of ground contact from heel strike to the middle of mid-stance when the tibia first becomes perpendicular with the foot. Contact 2 spans the second half of ground contact, beginning when the tibia first becomes perpendicular with the foot and ending at toe-off when the leg first loses contact with the ground. Finally, the Swing state spans the entire swing phase, from toe-off to heel strike.

[0030] In a Contact 1 state, from heel strike to midstance, the objective of the controller is to prevent foot slap. During a Contact 2 state, from midstance to toe-off, the controller minimizes the impedance of the brace so as not to impede power plantar flexion movements. Finally, in a Swing state, spanning the entire swing phase, the user's foot is lifted to